Report from the Dark Matter Group:

October 7, 2015

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Dark Matter Science Drivers

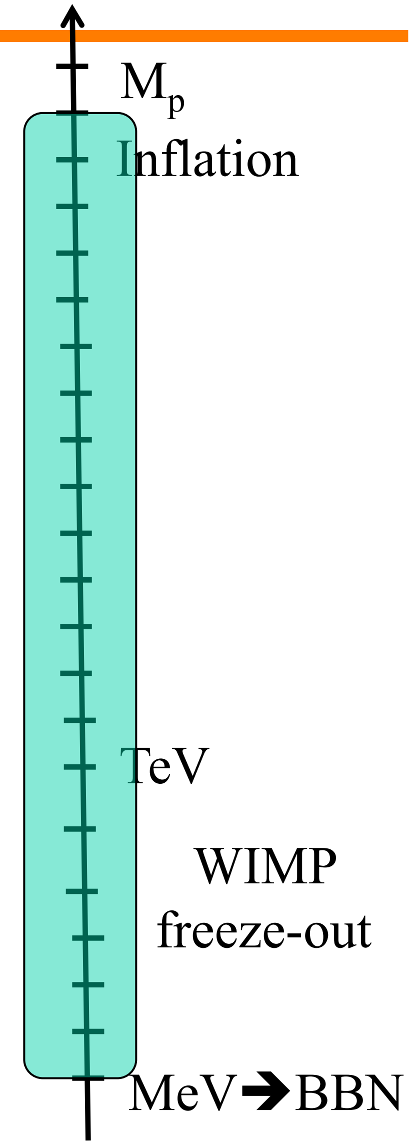
DM Science cuts across technologies

We are looking for something we know is there, but because we do not know what its particle properties are, we need to cast the net wide. Models tend to direct our technology choices.

Promising candidates: WIMPs and Axions, but other possibilities cannot be neglected

Characterized by breadth of technique and Complementarity

Direct and Indirect Detection, Collider Production



Relevant Presentations

- **Matt Pyle plenary: Theory and Detector Design Drivers**
- **Bhaskar Dutta: Dark Matter – Direct, Indirect, Colliders**
- **Oliver Buchmueller – Dark Matter at the LHC**
- **Eric Charles – Indirect Detection of Dark Matter**
- **Louis Strigari – Neutrinos in Dark Matter Detectors**

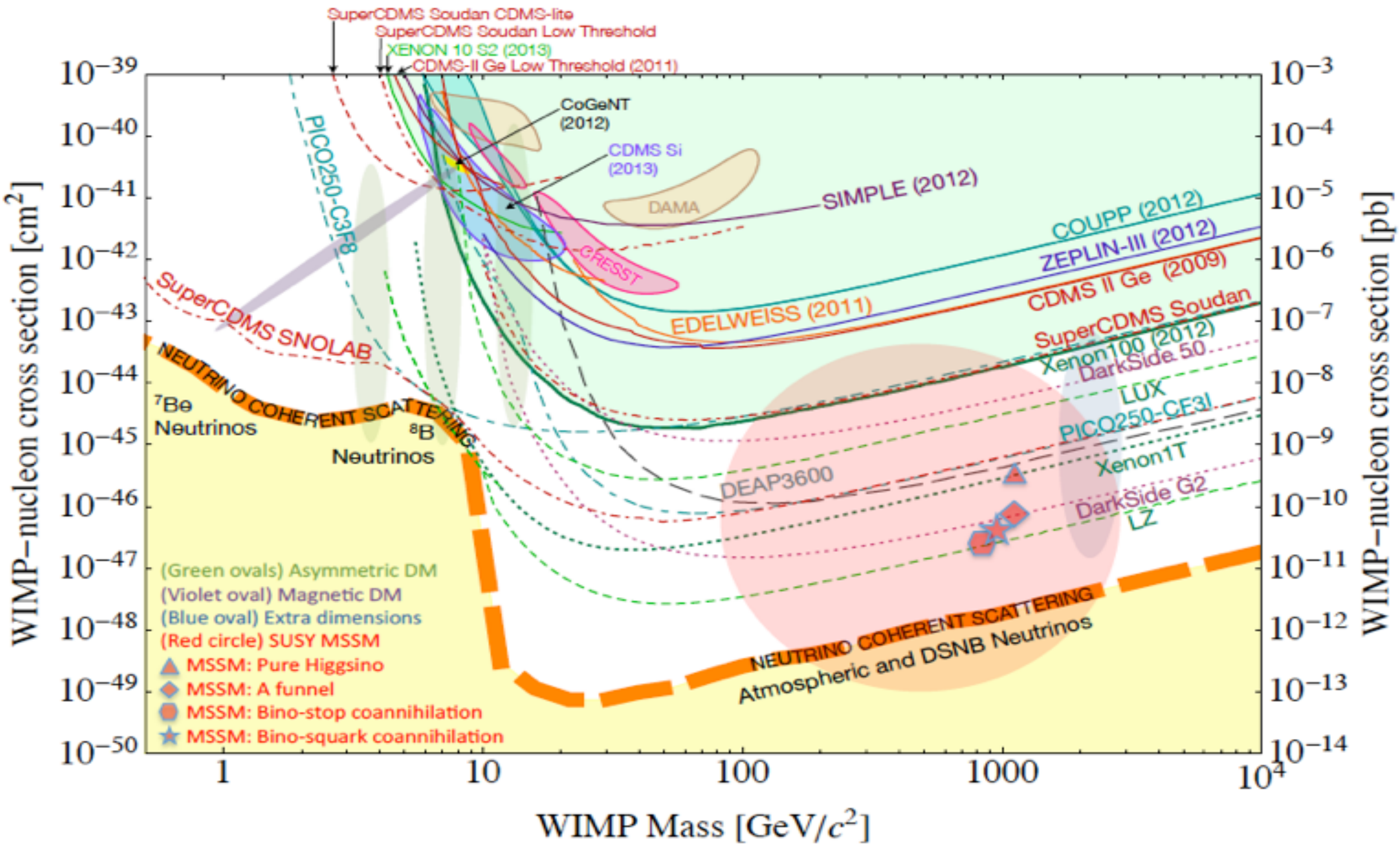
Joint Session: Dark Matter and Exploring the Unknown

- **G. Carosi – Future of Axion Searches**
- **Jeremy Mardon – Future of Dark Sector Searches**
- **Surjeet Rajendran – Ultra-light Dark Matter**

This summary talk can't do justice to the full scope and needs of the dark matter science. The detailed report will!

Direct Detection of WIMP dark Matter

- The neutrino floor represents a goal for the G2 and G3 experiments
- G2 = Some complementarity of targets between 1 – 1000 GeV/c^2



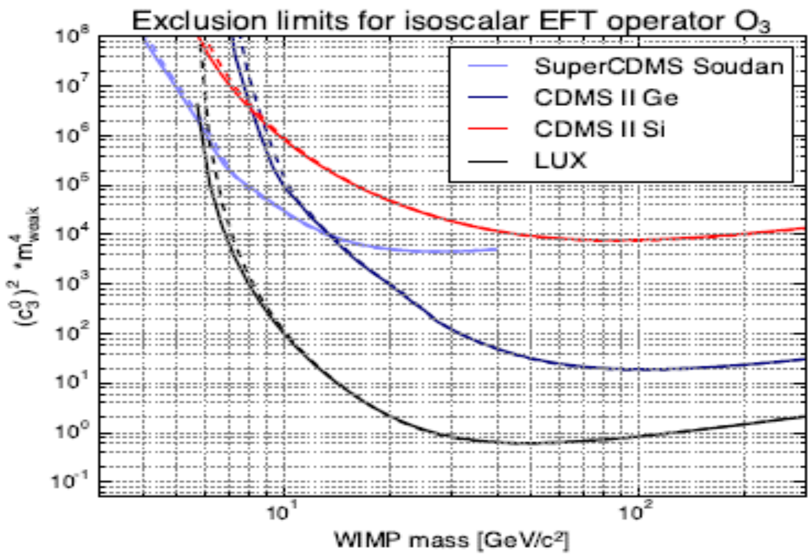
Findings: Need Complementarity of Targets if we want to probe interaction physics

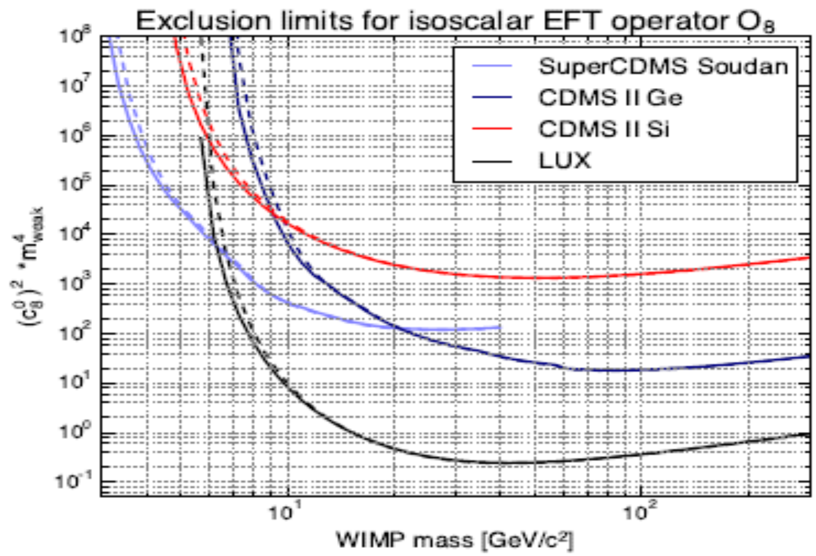
Future prospects for distinguishing models

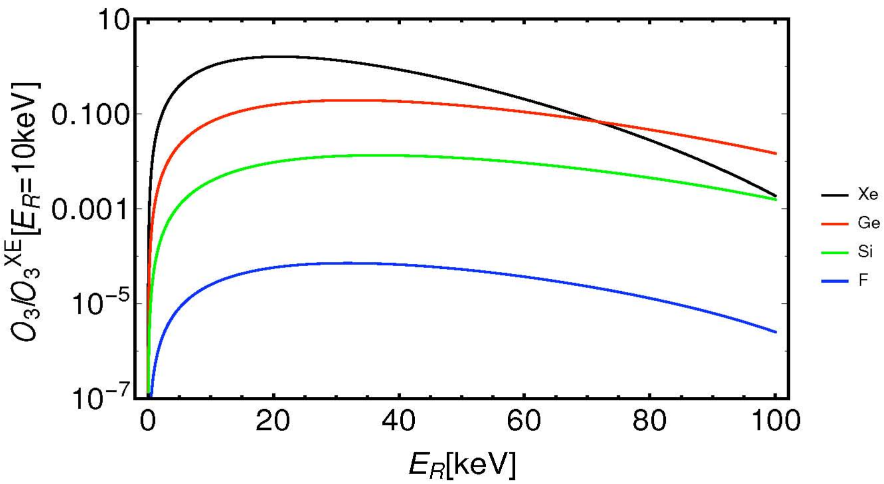
V. Glusevic, M. Gresham, S.D. McDermott, A.H.G. Peter, and K. Zurek, arXiv:1506.04454

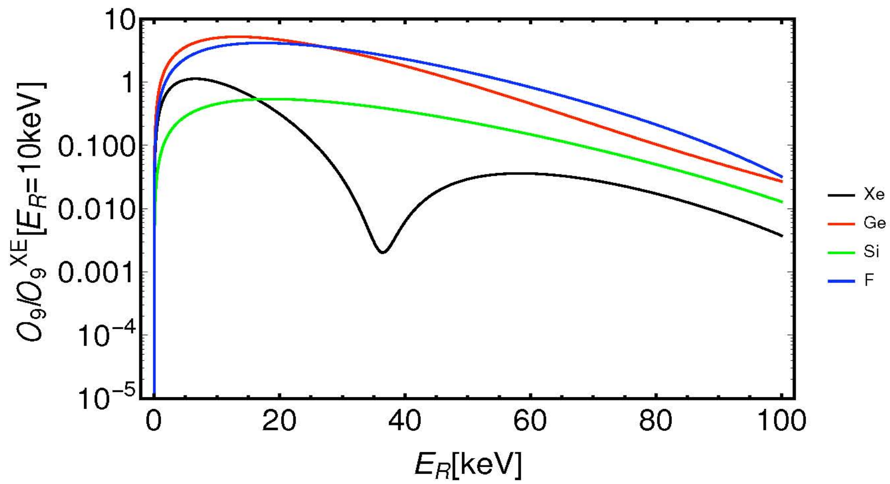
Model name	Lagrangian	$\vec{q}$, v Dependence	Response	f_n/f_p
SI	$\bar{\chi}\chi\bar{N}N$	1	M	$+1$
SD	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$	1	$\Sigma' + \Sigma''$	-1.1
Anapole	$\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$	$v^{\perp 2}$ $\vec{q}^2/m_N^2$	M $\Delta + \Sigma'$	photon–like
Millicharge	$\bar{\chi}\gamma^\mu\chi A_\mu$	$m_N^2 m_\chi^2/\vec{q}^4$	M	photon–like
MD (light med.)	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	$1 + \frac{v^{\perp 2} m_N^2}{\vec{q}^2}$ 1	M $\Delta + \Sigma'$	photon–like
ED (light med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi F_{\mu\nu}$	$m_N^2/\vec{q}^2$	M	photon–like
MD (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\frac{\vec{q}^4}{\Lambda^4} + \frac{v^{\perp 2} m_N^2 \vec{q}^2}{\Lambda^4}$ $\vec{q}^4/\Lambda^4$	M $\Delta + \Sigma'$	photon–like
ED (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\vec{q}^2 m_N^2/\Lambda^4$	M	photon–like
SI_{q^2}	$i\bar{\chi}\gamma_5\chi\bar{N}N$	$\vec{q}^2/m_\chi^2$	M	$+1$
SD_{q^2} (Higgs-like/flavor–univ.)	$i\bar{\chi}\chi\bar{N}\gamma_5 N$	$\vec{q}^2/m_N^2$	Σ''	$+1/-0.05$
SD_{q^4} (Higgs-like/flavor–univ.)	$\bar{\chi}\gamma_5\chi\bar{N}\gamma_5 N$	$\vec{q}^4/m_\chi^2 m_N^2$	Σ''	$+1/-0.05$
$\vec{L}\cdot\vec{S}$-like	$\bar{\chi}\gamma_\mu\chi\frac{\partial^2\bar{N}\gamma^\mu N}{m_N^2} +$ $+\bar{\chi}\gamma_\mu\chi\frac{\partial_\nu\bar{N}\sigma^{\mu\nu}N}{2m_N}$	$\vec{q}^4/m_N^4$ $\vec{q}^4/m_N^4$ $\frac{\vec{q}^2 v^{\perp 2}}{m_N^2} + \frac{\vec{q}^4}{m_\chi^2 m_N^2}$	M Φ'' Σ'	$+1$

Simulated over 8000 recoil energy spectra for various models







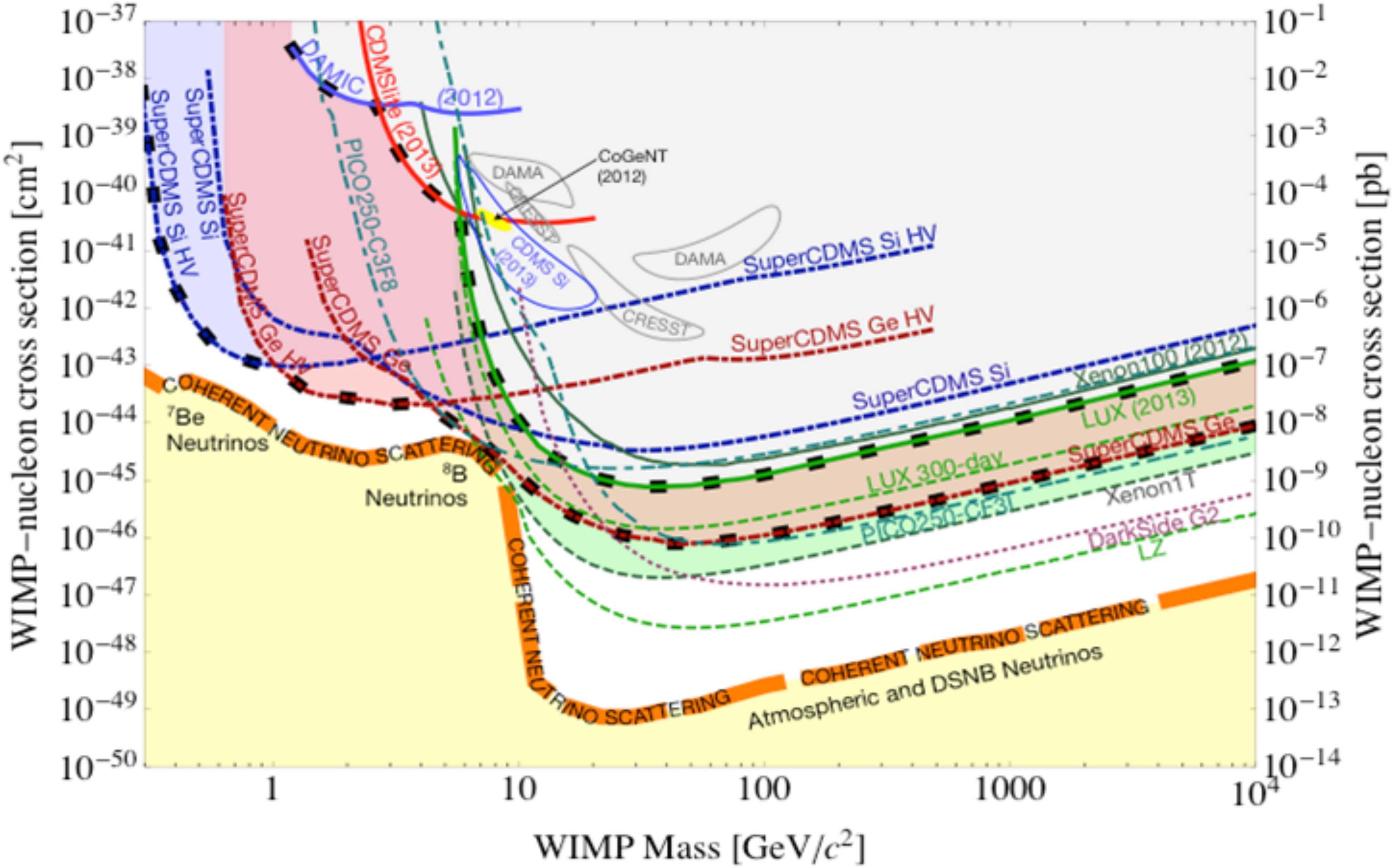


$\mathcal{O}_3$ $\quad i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right)$ $\qquad \mathcal{O}_9$ $\quad i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$

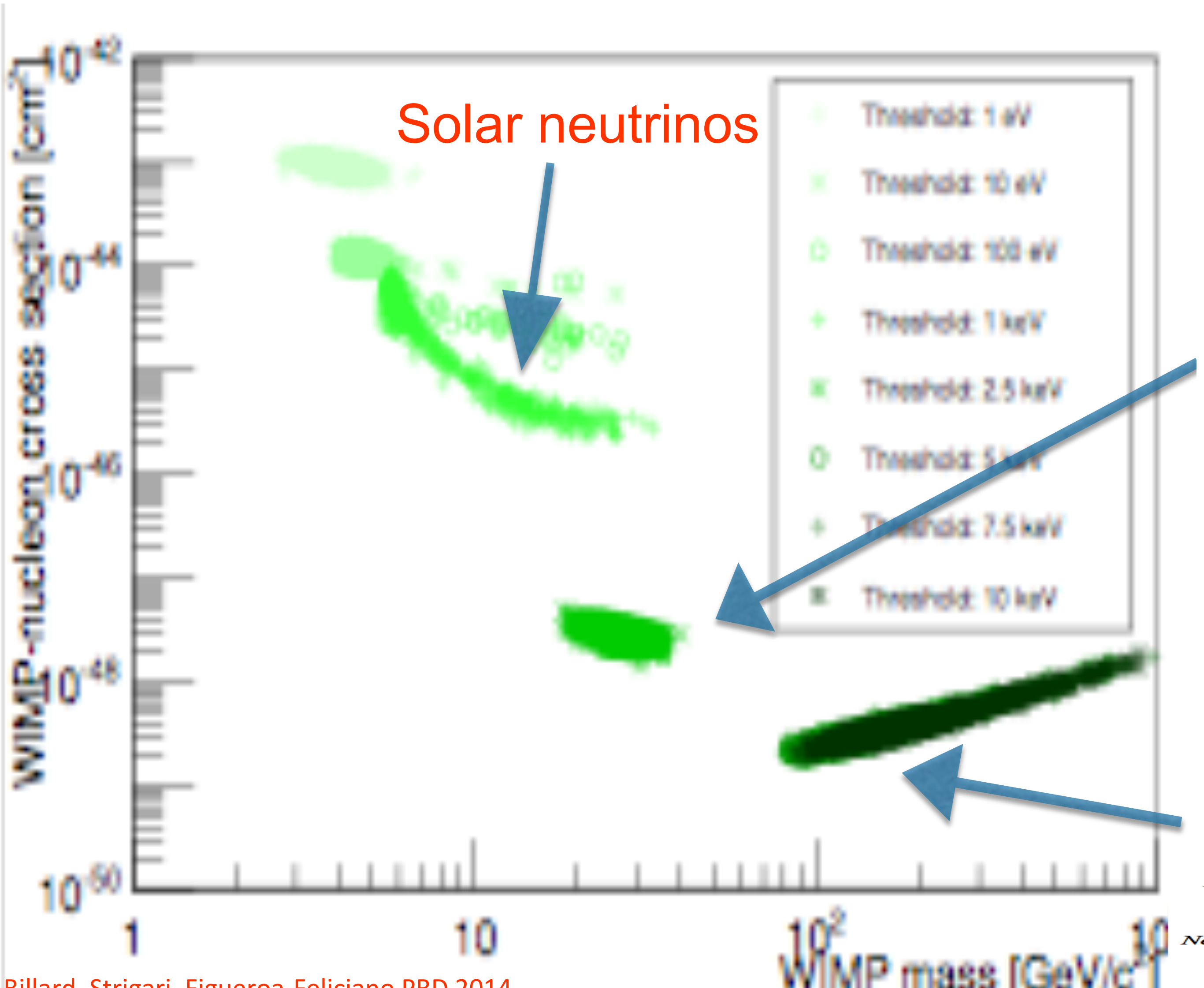
A complementary choice of nuclear targets can provide important discriminating information

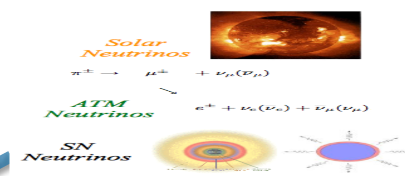
Going Beyond the Neutrino Floor in G3 Experiments

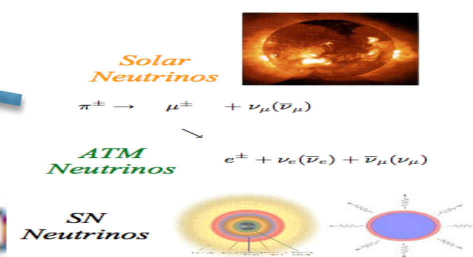
Precision measurement of CNS would provide ability to do statistical subtraction – solar neutrino most feasible in the next decade
Spectroscpic differences in recoil spectrum? Annual modulation?



Can neutrinos mimic the WIMP signal?







Billard, Strigari, Figueroa-Feliciano PRD 2014

Going beyond the neutrino background: Non-relativistic EFT

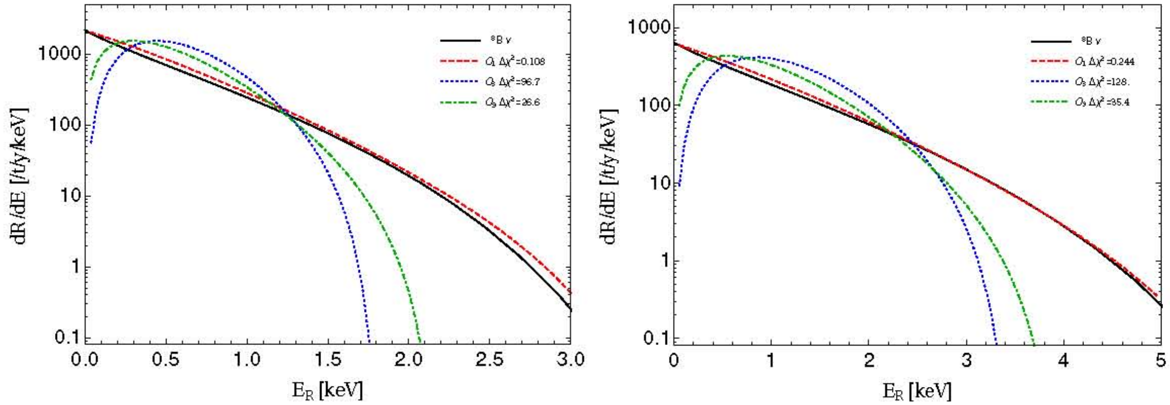


FIG. 2. Sample max likelihood rates fit to the boron-8 neutrino rate in xenon (left) and germaniur (right)

Target	threshold (low/high)
xenon	3.0 eV / 4.0 keV
germanium	5.3 eV / 7.9 keV

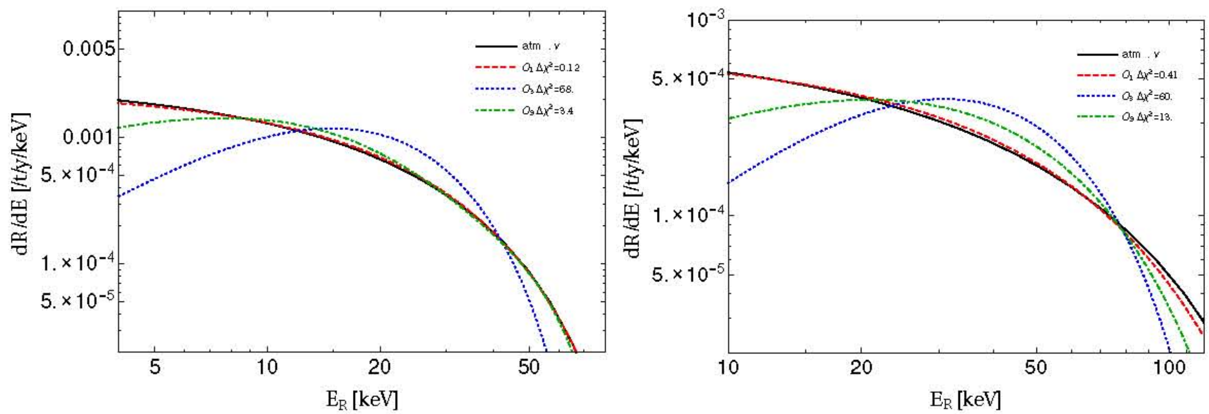
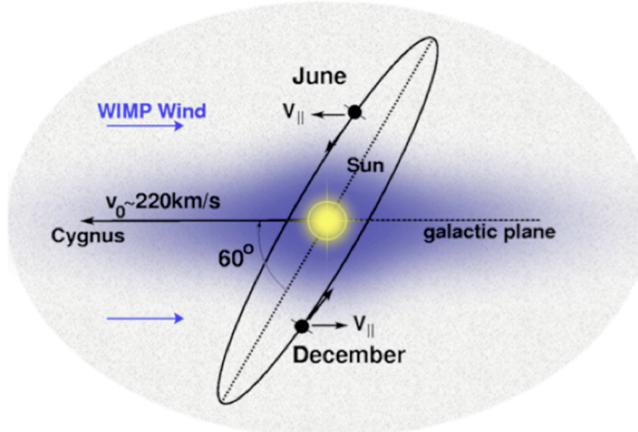


FIG. 3. Sample max likelihood rates fit to the atmospheric neutrino rate in xenon (left) and germanium (right)

Dent, Dutta, Newstead, and Strigari to appear

Going beyond neutrino background: Directional detection

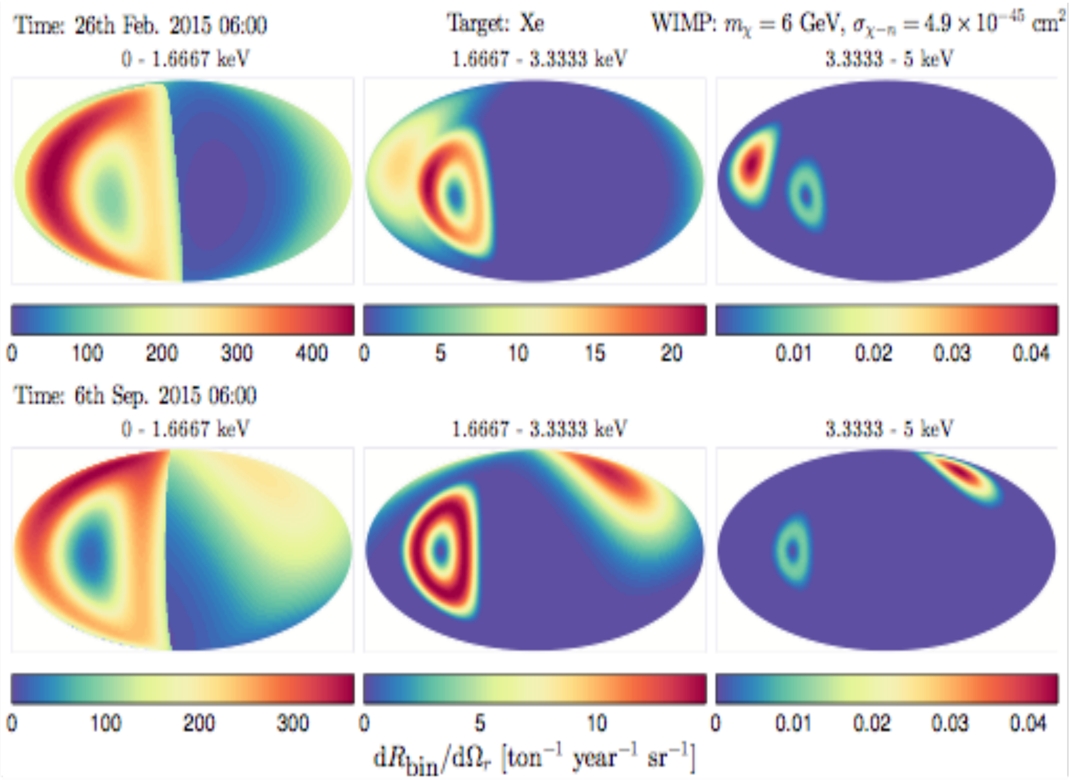


$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 E_\nu^2 (1+\cos\theta) F(Q^2)^2$$

WIMP signal points to the direction of Cygnus

Direction to the Sun and Cygnus do not overlap during the year

Directionality can cleanly separate the WIMP from the Solar neutrino signal



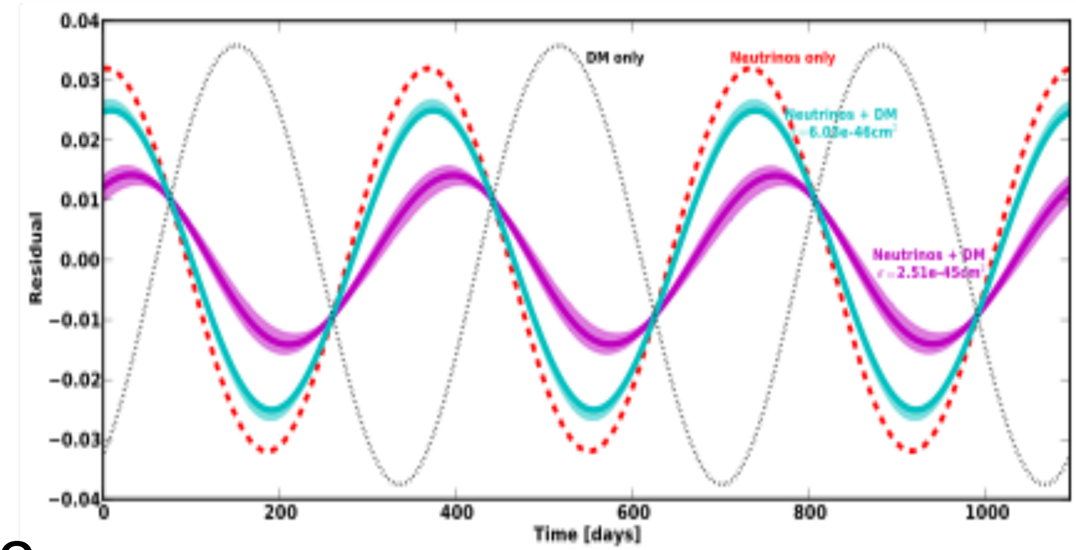
Grothaus et al. 2014; O'Hare, Billard, Green, Figueroa-Feliciano, Strigari PRD 2015

Going beyond the neutrino background: Annual modulation

Annual modulation of WIMP signal due to orbit of Earth around Sun

Solar neutrino flux varies by a few % per year due to eccentricity of the Earth's orbit

~10,000 Solar neutrino events required to distinguish time variation of Solar neutrinos from WIMPs

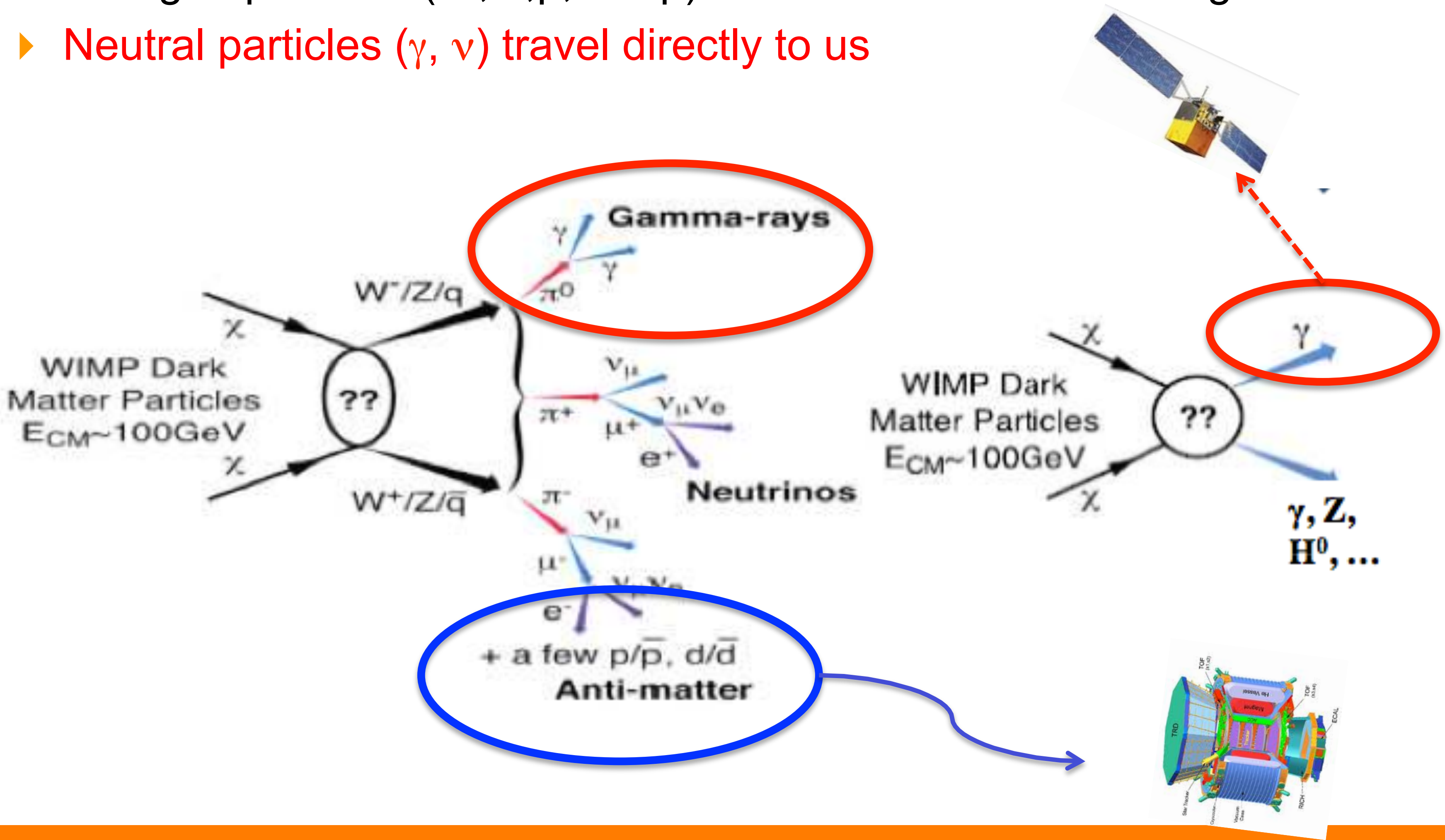


J. Davis 2014; O'Hare, Billard, Green, Figueroa-Feliciano, Strigari PRD 2015

Indirect Detection of WIMP dark Matter

What we observe are stable final-state annihilation products

- Charged particles (e^+,e^-,p,anti-p) diffuse in the Galactic magnetic field
- Neutral particles (γ, ν) travel directly to us



Findings: Many strategies. Go where the WIMPs concentrate

Satellites

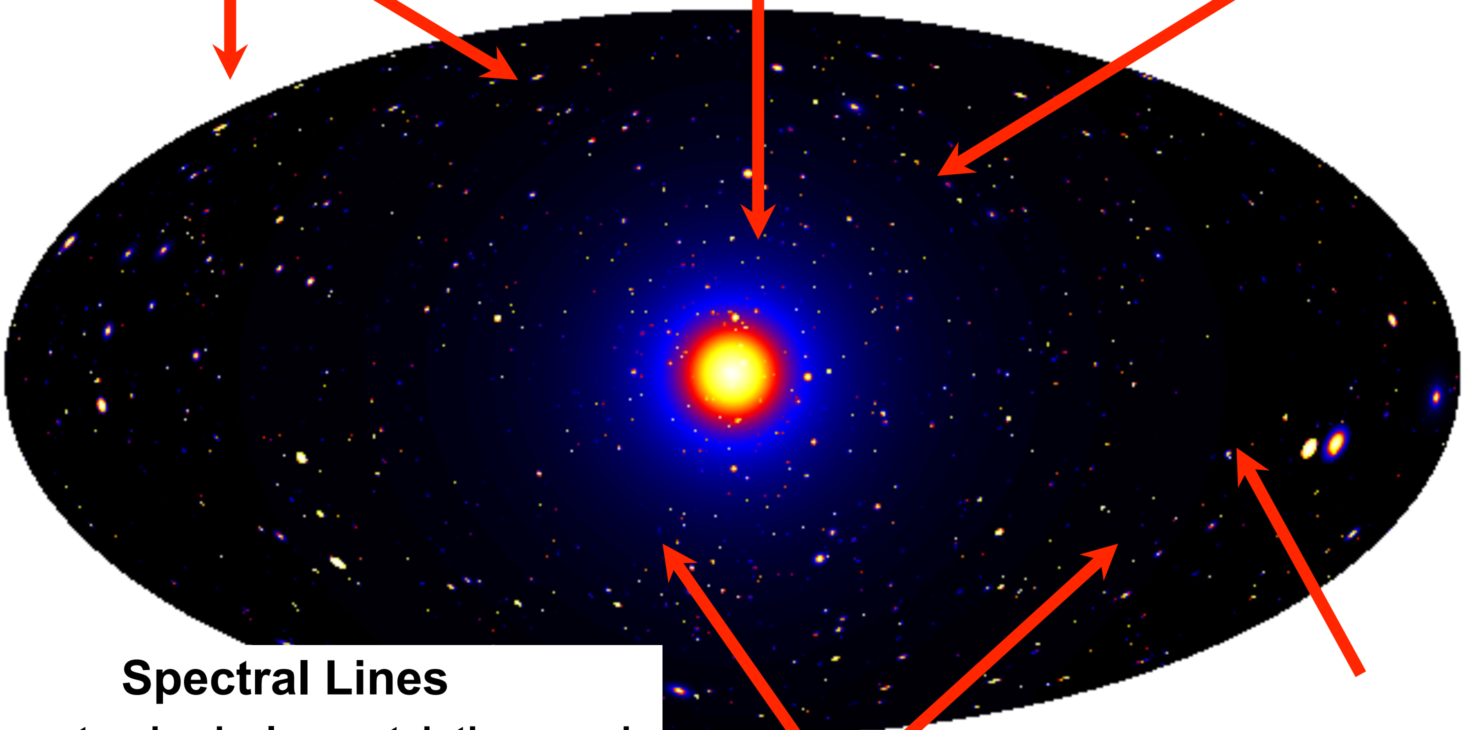
Low background and good source id, but low statistics

Galactic Center

Good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

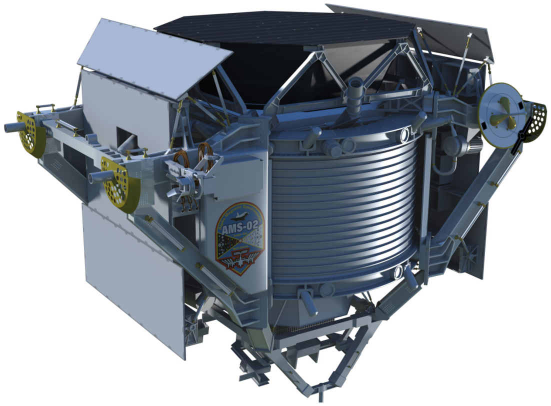
Galaxy Clusters

Low background, but low statistics

Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

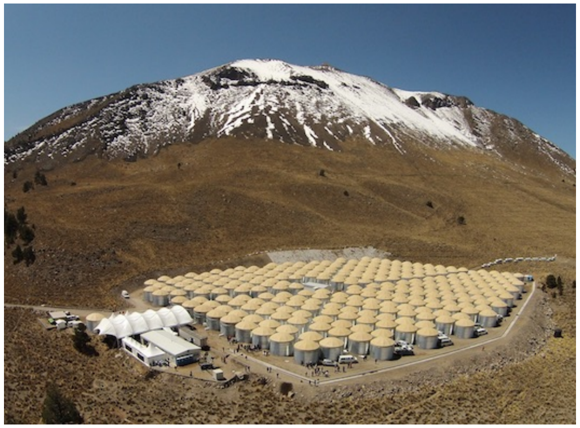
Healthy program of ground-based and space-based detectors, multi-messenger approach

Pair-conversion telescopes:
Fermi, *AGILE*, *DAMPE*,
Gamma-400

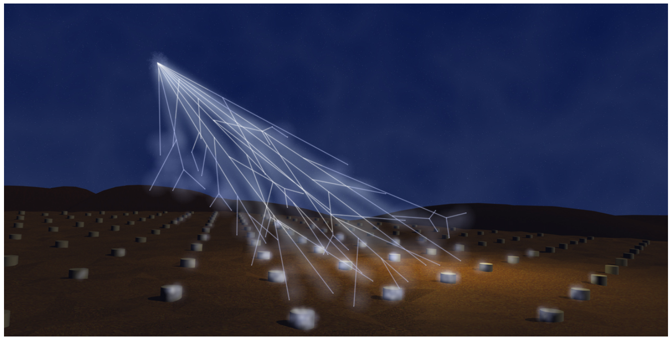


Cosmic-ray detectors:
PAMELA, *AMS-02*, *HERD*

Imaging Atmospheric Cherenkov Telescopes:
HESS, *MAGIC*, *VERITAS*,
CTA



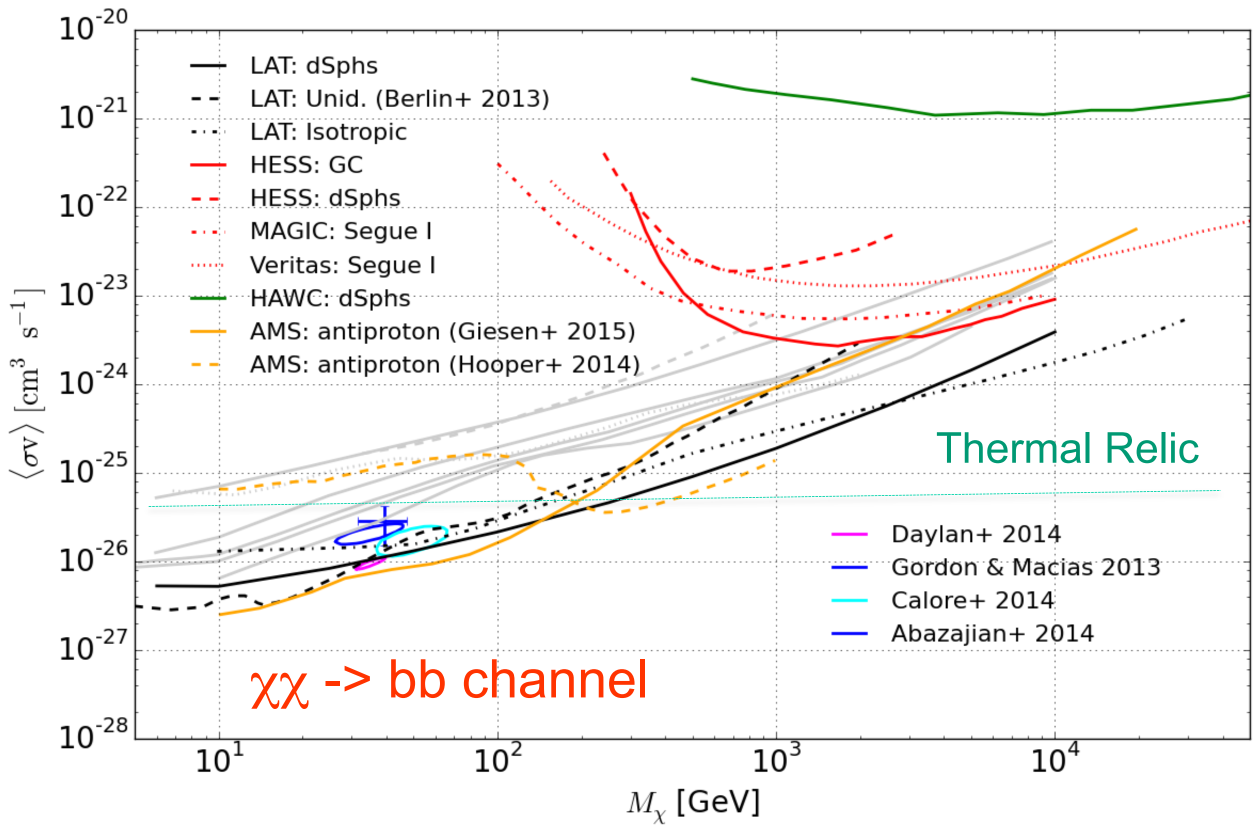
Water Cherenkov Telescopes:
HAWC, *ICE-Cube*



Hybrid cosmic-ray detectors:
Auger

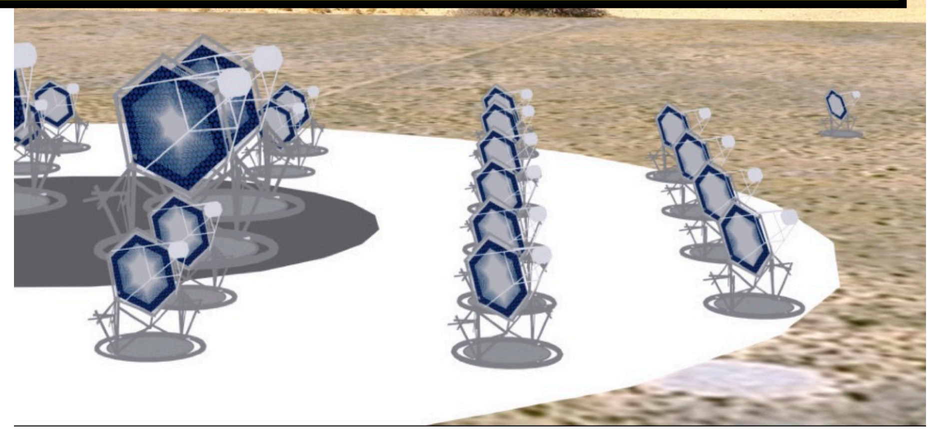
Findings:

- Limits from many experiments are now very sensitive
- DM hints often have conventional explanations.
- Astrophysics is necessary to understand backgrounds and to interpret enhancements.



Driving Factors in Instrument Development

In both cases we are pushed toward modifying well-established technology to meet the instrument design challenges & optimize scientific return.



- *Space-based*: performance constrained by mass (~< 10000 kg), power budget (~< 3kW), bandwidth (~< 10 MHz averaged). Must survive launch (vibrational / acoustic noise), space radiation environment.

- *Ground-based*: performance constrained by light collection area, array size and in-fill factor, (air-showers arrays: night-sky brightness)

Non-WIMP dark matter: Types of bosons

Naturalness. Structure set by symmetries.

Spin 0
Axions or ultra weak coupling
Many UV theories

Spin 1
Anomaly free
Standard Model couplings

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E&M	QCD	Spin	Higgs	Spin	E&M	Current
$\left(\frac{a}{f_a}F\tilde{F}\right)$	$\left(\frac{a}{f_a}G\tilde{G}\right)$	$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$	$\left(g\phi H^2\right)$	$\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}N\right)$	$\left(\epsilon F' F\right)$	$\left(g A'_\mu J^\mu_{B-L}\right)$
Current Searches (m_a ~ GHz)	QCD Axion	General Axions	Higgs Portal/ Relaxion	Dipole moment	Kinetic Mixing	B-L

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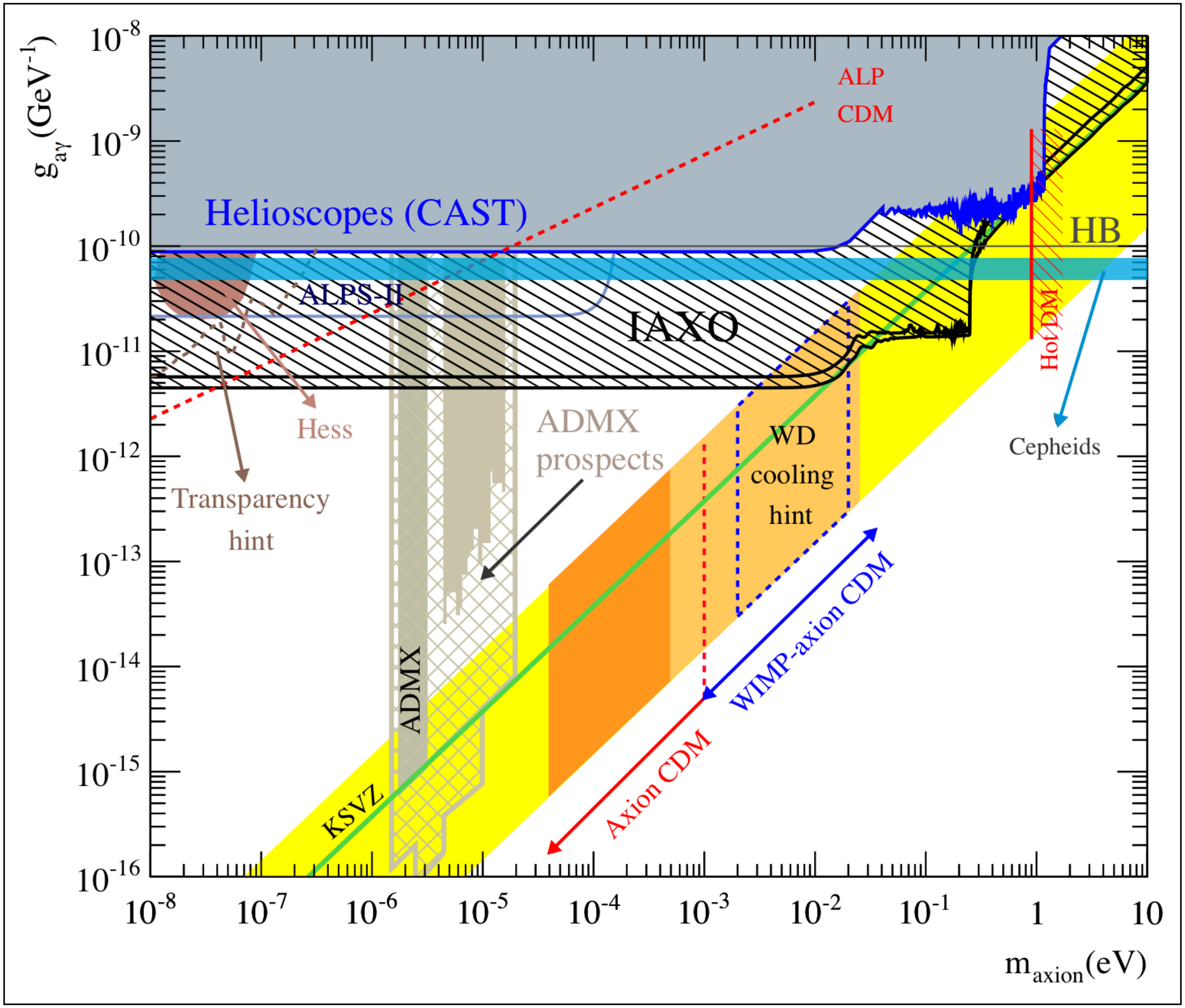
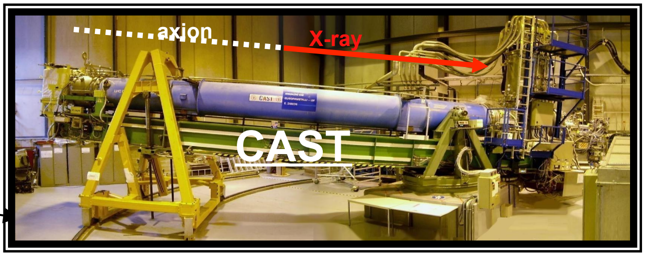


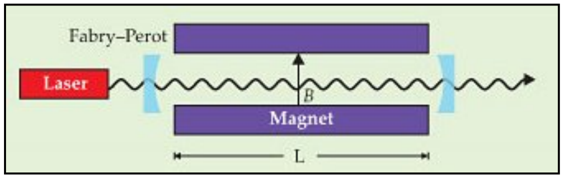
Helioscopes (CAST)
ALP
CDM
HB
ALPS-II
IAXO
Hot DM
Hess
Transparency
hint
ADMX
prospects
ADMX
WD
cooling
hint
Cepheids
KSVZ
Axion CDM
WIMP-axion CDM
$g_{a\gamma}$ (GeV^{-1})
m_{axion}(eV)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

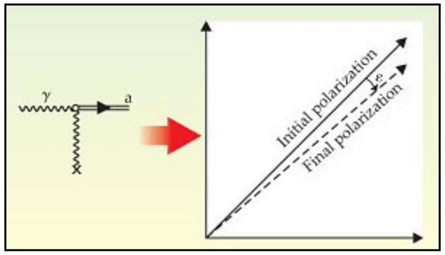
Axions from DM, Sun, relic ALPs, lasers

- Solve strong-CP problem and are a compelling DM candidate
- <u>Microwave Cavities (dark matter source)</u>
  - Low noise amplifiers (**ADMX**) and Rubidium Atoms (**CARRACK**)
    - —Look for dark matter axions (low mass) converting to photons in B-Field
    - —**Relies on a dense source of primordial axions**



- <u>Solar Observatories (solar source)</u>
  - X-Ray (**CAST**) and Germanium detectors
    - —Look for axions generated from the sun
    - —Higher coupling required than for DM axions.
- <u>Lab experiments (laser source)</u>
  - Photon regeneration and polarization changes (**PVLAS**)
    - —Look for production of axions from light passing through B-field
    - —Higher coupling required.
    - —Ultralight axions (nano-eV) (NMR / LC Circuit)





The Importance of Low Noise Temperature

- Original system noise temperature: $T_S = T + T_N = 3.2$ K

  Cavity temperature: $T = 1.5$ K (pumped ^{4}He)

  Amplifier noise temperature: $T_N = 1.7$ K (HEMT)

- Time* to scan the frequency range from $f_1 = 0.5$ to $f_2 = 1$ GHz:

$$\tau(f_1,f_2) = 4 \text{ x } 10^{17}(3.2\text{K}/1\text{ K})^2(1/f_1 - 1/f_2) \text{ sec} \approx \mathbf{130\ years}$$

- Next generation:

  Cavity temperature: T = 100 mK (^{3}He dilution unit)

  Amplifier noise temperature: $T_N = 50$ mK (MSA)

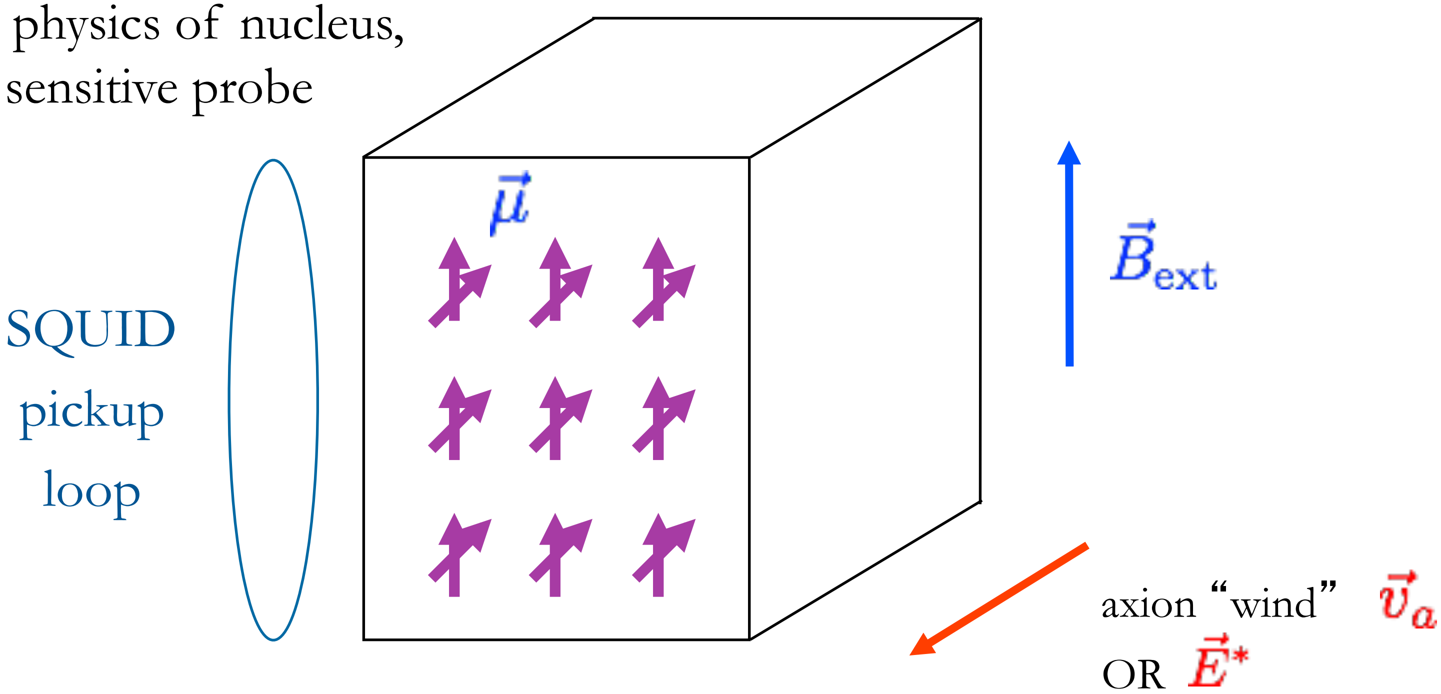
- Time* to scan the frequency range from $f_1 = 0.5$ to $f_2 = 1$ GHz:

$$\tau(f_1,f_2) = 4 \text{ x } 10^{17}(0.15\text{K}/1\text{ K})^2(1/f_1 - 1/f_2) \text{ sec} \approx \mathbf{104\ days}$$

*Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) theory

CASPEr

Axion affects physics of nucleus,
NMR is sensitive probe



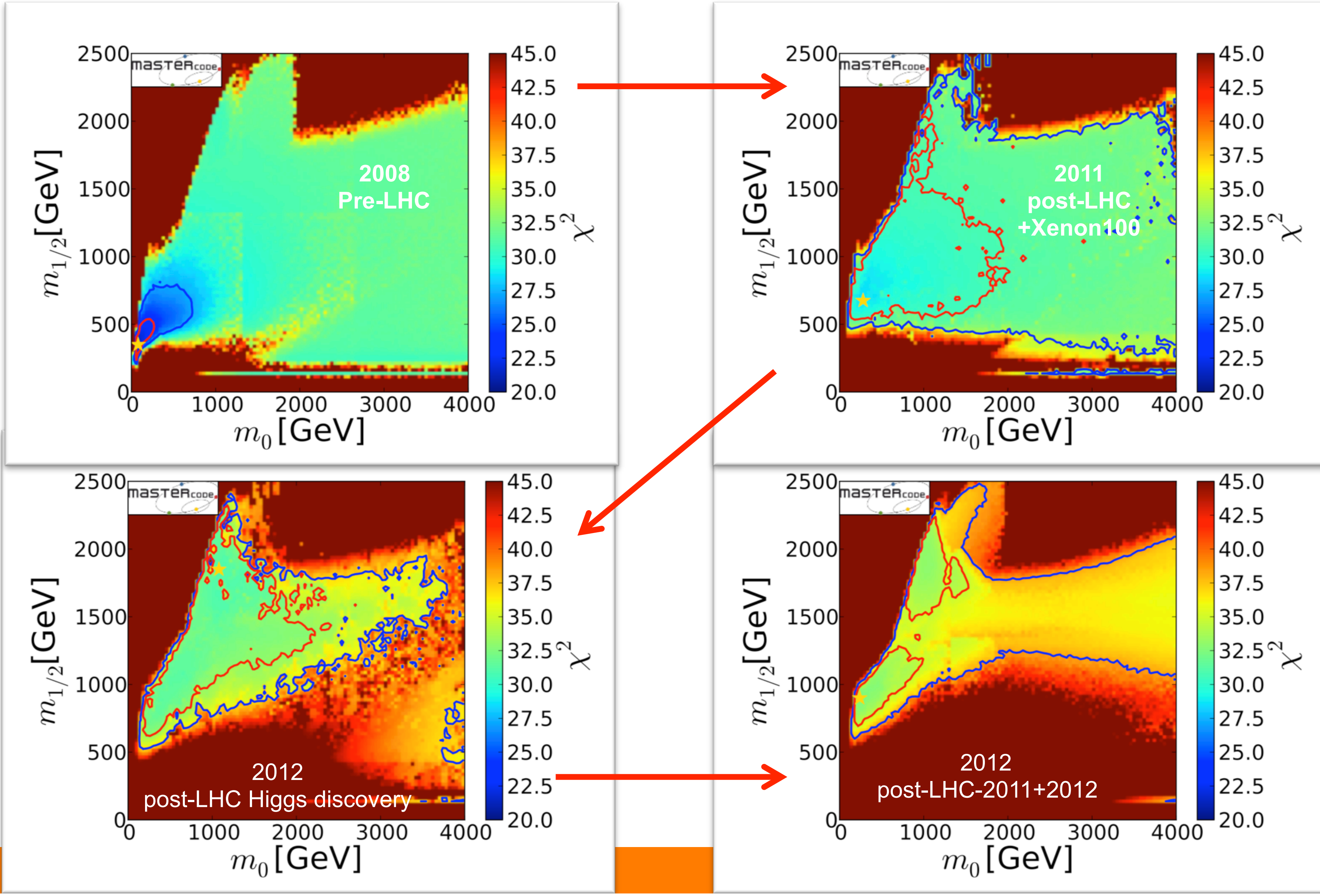
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

NMR well established technology, noise understood, similar setup to previous experiments

Example materials: LXe, ferroelectric $PbTiO_3$, many others

CMSSM: Evolution with time



LHC, Direct, Indirect, DM content

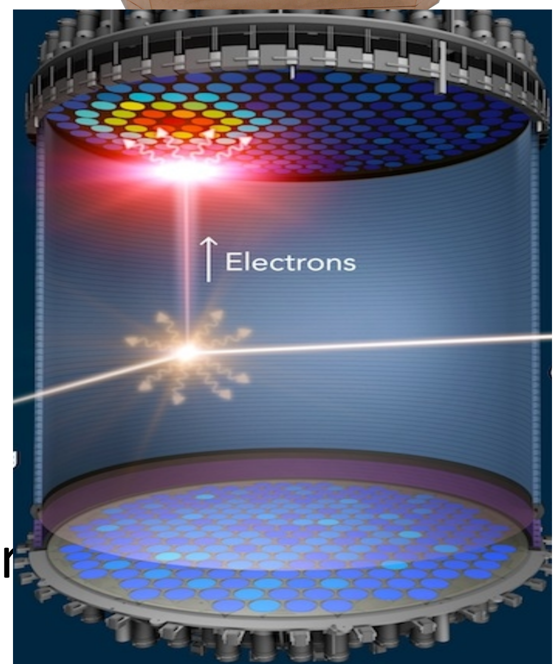
$$\widetilde{\chi}_1^0 = f(\widetilde{B}, \widetilde{W}, \widetilde{H}_u, \widetilde{H}_d)$$

	Wino	Higgsino	Bino	Higgsino-Bino
Indirect	good	good	ok	good/ok
LHC	good	good	poor	ok
DM Content	NT/mixed	NT/mixed	T/NT	T/NT
Direct	poor	good(SD)	poor	good(SI)

NT: Non-thermal, T: Thermal

Grand Challenges for Direct Detection

- Detector development - Details in Detector Session
  - Need massive low threshold detectors
  - Large Directional Detectors to cut down background
- Confirm signal through a different target
  - If LZ and Xenon1T find signal, need Ge/Si/Ar to confirm
- Background Discrimination
  - All experiments need continuing improvements
- Background Reduction
  - including Radon mitigation and surface screening
  - Access to radiopure materials and assay resources
- Low energy calibration Calibration
  - Robust NR calibration is difficult and needs support
- High synergy between 2 β decay and DM detector
  - HEP+NP? HPGe Radiopurity, Shielding, electronics..



Grand Challenges for Indirect Detection

- Pair-conversion telescopes:
  - More collecting area (bigger). Larger field-of-view (monolithic tech?)
- Instrumental R&D will likely focus primarily on scaling existing technologies for use in future instruments
  - *Cost per channel, data volume and rate, and instrument infrastructure*
  - *Space-based instruments have the additional constraints (e.g. power)*
- Adapt existing technologies for scalable, low-cost, applications
  - Need seed funding from DOE to prove ideas to finally propose to NASA
- Design of next-generation instruments for indirect DM searches will focus on scalability issues such as:
  - *Building a pair-telescope with 25 m^2sr acceptance*
  - *Infilling CTA to better image the entire air-shower*
- Main room for improvement for IACTs:
  - Better γ-hadron separation (more telescopes, greater infill)

Grand Challenges for Axion Searches

- Microwave Cavities:
  - High-Frequency, Large-Volume Tunable Systems with high Q
- RF Detectors: Quantum Limited (0.25 – 10 GHz)
  - SQUIDs & JPAs
- Beyond several GHz standard quantum limit begins to dominate
  - Employ Squeezed States and Eventually Single-Photon-Counters
- Large Magnets can increase axion conversion signal.

Grand Challenges for Collider DM Searches

- Many details in technology sessions, especially in detectors and trigger/DAQ
- How to combine collider results with that from direct and indirect searches. Some failures – mono-jet event interpretations, EFT theory uses for low mediator masses